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MATERIALS FOR HYPERSONIC ENGINES

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SUMMARY

This paper describes the structural materials development program for the National Aero-Space Plane (NASP). It indicates the materials studied, the approaches followed, and the general properties being developed. The major materials classes include titanium-aluminides, titanium-aluminide metal matrix composites, carbon-carbon composites, ceramic-matrix composites, beryllium alloys and copper-matrix composites.

PREFACE

The U.S. National Aerospace Plane Program (NASP) is developing the technologies that are considered to be key to the successful operation of hypersonic aerospace vehicles. The general goal of the NASP program is the construction and testing of an experimental, fully reusable vehicle, designated the X-30, that will be used as a manned demonstrator of hypersonic flight. The vehicle will use hydrogen-fueled, air-breathing ramjet/scramjet engines and will be capable of horizontal take-off and landing. It will be designed to expand the envelope of high speed flight in and beyond the atmosphere to the point that access to low earth orbit can be achieved.

To meet weight and performance requirements, the NASP X-30 engines and airframe will make extensive use of uninsulated, load-bearing, lightweight structures. Active cooling with the hydrogen fuel will be used in many cases to keep temperatures within the capabilities of the materials, but to minimize weight it will be vital to have materials that combine low density with the highest possible temperature performance. Because of their potential for satisfying these needs, the materials classes of primary interest include titanium-aluminides, titanium-based metal-matrix composites, carbon-carbon composites, ceramic-matrix composites, copper-matrix composites and beryllium alloys.

The required materials and structures developments have been the subject of an extensive $150 million program that started in March 1988. Known formally as the NASP Materials and Structures Augmentation Program, it is a cooperative venture of the five prime contractors who are developing concepts for the NASP airframe and engines. In addition to these five companies, the program uses the active participation of more than a hundred specialist subcontractors in addressing the various materials and processes development needs. The scope of the development program extends to the fabrication and testing of full-scale demonstration components of the various materials systems.

Each of the five prime contractors has undertaken the lead role for the development of one of five key classes of materials, with each company participating in the development activities for all five classes. General Dynamics heads the refractory composites area, involving carbon-carbon composites and ceramic-matrix composites. Rockwell has taken the lead for the titanium-aluminide development and scale-up effort, based on the Ti_3Al and TiAl classes of materials. McDonnell Douglas manages the effort on titanium metal-matrix composites, comprising fiber-reinforced titanium alloys and Ti_3Al intermetallics. Rocketdyne has the responsibility for high conductivity materials, comprising copper-matrix composites and beryllium alloys. Pratt and Whitney has undertaken the high creep strength materials activity, involving materials and structures intended for hot, actively cooled engine components. This latter area centers on monolithic and reinforced TiAl, using potentially compatible fibers such as titanium diboride.

Almost all of these materials are potentially important for hot, load-bearing structures in both the airframe as well as the engines of the vehicle. On the airframe they would be used as lightweight skin panels of honeycomb-core, truss-core, or integrally stiffened thin sheet configuration. Where necessary they would be cooled with the hydrogen fuel by incorporating appropriate coolant passages into the structures. In the engines they would be used as the sidewall panels in the hot gas path of the ramjet/scramjet. The engine application represents a particularly severe environment in the sense of thermal, acoustic and mechanical loading. In this case the structures will almost certainly have to be actively cooled, meaning that the materials will be in contact with hot hydrogen from the fuel, hot oxygen from the incoming air, and the gaseous products of combustion.

The remainder of the paper describes the various classes of materials that are under development. Because they will find application over all of the vehicle, little distinction is made between the engine and the airframe needs. The general materials classes and associated processes apply equally to all areas, whether they are the small hot gas path panels of the engines or the more extensive regions of the airframe. The specific property requirements will be different--for example, time at temperature--but the materials themselves are not in general engine- or airframe-specific.

TITANIUM ALUMINIDES

Titanium-aluminide intermetallics are candidates for structures in both the engines and the airframe. They have essentially the same density as titanium but lead to the possibility of much higher use-temperatures. The two intermetallic systems that are of primary interest are based on the Ti_3Al and TiAl compositions and have potential temperature capabilities of about 815°C and 980°C respectively.

The principal drawback of the aluminides is their limited ductility and toughness properties at temperatures less than a few hundred degrees. Coupled with the requirement for very high fabrication temperatures, this makes their processing difficult. Product forms that require a large amount of metal deformation, such as sheet for honeycomb-core or truss-core panels, must be processed in a carefully controlled manner to avoid cracking of the material during the reduction of the starting material to finished form. In addition, the use of the aluminide components in load-bearing structures must take account of the probability that their ductility and toughness characteristics will be limited in comparison to other materials, such as conventional titanium alloys.

New processing methods are being used to modify aluminide compositions and microstructures to yield structurally useful materials. The goal is to achieve an appropriate balance of strength with toughness or ductility while retaining the low density and high temperature characteristics that make the aluminides so attractive. One useful approach that has been quite successful employs rapid-solidification powder methods to develop improved alloys and much of the NASP-related work in this area uses a rotary atomization process to produce rapidly solidified powder. The powder is consolidated into fully dense billets that are then processed into appropriate product forms. The process is now relatively mature and the equipment has been scaled up to the point that it is capable of making hundreds of kilograms of powder material a day.

Advanced thermal-mechanical processing methods have been developed for both the powder-produced intermetallics and those made using conventional cast and wrought methods. These processes have improved the characteristics of the Ti_3Al-based alloys significantly and good quality sheet products are being produced. Sheet-processing methods for the harder-to-work TiAl-based materials have also been developed but have yet to be scaled up to an economical production level. In terms of mechanical properties, significant improvements have been made in the Ti_3Al-based materials and they can be regarded as good candidates for broad structural use. In the TiAl materials, a balanced set of mechanical properties--a suitable mix of strength, toughness, ductility, fatigue, and high temperature properties--is still to be achieved.

Because much of the airframe and engine structure will be actively cooled, hydrogen at various temperatures and pressures will be in contact with many of the structural materials. Hydrogen interacts adversely with most titanium alloys, leading to embrittlement in many situations, but the titanium aluminides are more resistant than conventional alloys, with the TiAl materials being the least affected. Hydrogen-resistant barrier coatings will be needed for all the materials to some extent, and the development of effective coatings is an integral part of the program.

TITANIUM ALUMINIDE COMPOSITES

Metal-matrix composites based on titanium-aluminides offer significant improvements in stiffness and strength over their monolithic counterparts, making them attractive for the thin-gauge skin structures required for NASP. The basic technical challenge in making these composites is to incorporate reinforcement fibers into the matrix without creating adverse reactions at the fiber/matrix interface.

The conventional method for fabricating metal-matrix composites--involving the hot pressing of sandwiches of matrix material and fibers--is difficult to accomplish with titanium-aluminides. They have poor formability characteristics and they interact with the fiber at the temperatures and times needed for consolidation. There is also a thermal expansion mismatch between the fiber and the matrix that can lead to cracking of the low-ductility matrix on cooling from the consolidation temperature or during subsequent thermal cycling.

In an alternative approach to consolidation, a rapid-solidification plasma-deposition (RSPD) process is used to fabricate titanium-aluminide composites. The matrix material starts as a powder that is fed through a plasma arc to convert it into molten droplets. These are deposited onto reinforcing fibers that are spiral-wrapped on a large diameter drum, where on impact they are rapidly quenched to a solid state. Rotation and translation of the drum allows the build-up of a layer of matrix material on and between the fibers. This solidified deposit of matrix material, containing a single layer of fibers, can be subsequently slit and stripped off the drum and several of these layers can be stacked together and hot pressed to make a multilayer composite.

The RSPD process has been demonstrated successfully with SiC reinforcements in Ti_3Al matrix materials and useful mechanical properties can be obtained. The equipment itself has been scaled up to a pilot plant size that will allow the production of reinforced sheet material that is about 1x3 m in size. The same process can be used to produce TiAl-based composites but the inherent brittle nature of this material makes subsequent multi-layer consolidation difficult to achieve. This is principally the result of the thermal expansion mismatch between the fiber and the matrix that produces residual tensile stresses in the matrix on cooling, causing it to crack. Alternative fibers are under development that have a closer expansion match and better chemical compatibility to the TiAl matrix material than is the case with the SiC fiber. These appear to be promising but this class of composites will require further development to make them reliable structural materials.

XD COMPOSITES

The XD process can be applied to a variety of materials to form fine, close-spaced distributions of reinforcing second-phase particles. The term XD refers to the proprietary technique that is used to create the reinforcements. In essence, it is a process that results in the fabrication of discontinuously reinforced metal matrix composites where the matrix can be any one of a number of alloys and the reinforcing particles can be varied in terms of composition, size, shape and distribution. A unique feature of the process is that the reinforcements are formed and grown *in situ* within the matrix, as distinct from being mechanically mixed as a separate additive; as a result, the particle/matrix interfaces are clean and well bonded, thereby enhancing the effectiveness of the reinforcements.

The process can be tailored to produce a variety of second phase particle distributions, where the particle shape can vary from spherical to needle-like. Mixtures of different reinforcements also can be formed that include coexisting sizes, shapes and types of particles. In many cases, the dispersoids are very stable and can survive a remelting process; as a result, the material subsequently can be cast into shaped components without destroying the reinforcement.

The XD process has been used to make titanium aluminide composites where the reinforcing phase is titanium diboride. The microstructures resulting from the XD process are attractive principally because they lead to significantly improved strength levels over the useful temperature ranges of the aluminides. The properties are also essentially isotropic, making the materials useful for complex-shaped structures that would be difficult to fabricate from continuous fiber reinforced materials.

CARBON-CARBON COMPOSITES

Carbon-carbon composites have the potential for use as lightweight structures that could be exposed to temperatures in excess of 1400°C without the need for active cooling. Because of this capability, they are candidates for the airframe, where they could be used as large, integrally stiffened skin panels on the hotter parts of the vehicle. They may be useful also for engine structures.

In general, from the point of view of availability as structural shapes, carbon-carbon composites can be regarded as mature materials. There is a large base of knowledge available regarding their fabrication and practical use and they have been used in a variety of applications. Several companies specialize in the manufacturing of components and there are several basic methods available for making structural shapes.

There are technical problems to solve before they can be used as load-bearing, thin-gauge structural components for NASP. Chief among these is the need for effective oxidation protection in the hypersonic flight environment. Existing protection schemes, usually involving multilayer coatings and sealants, work reasonably well in situations where the material is taken up to a single high temperature and then cooled, but they face significant problems when exposed to complex temperature cycles.

The basic difficulty with existing protection schemes is their use of refractory materials such as silicon carbide as outer protection layers. These work well from a chemical standpoint but they can crack due to the thermal expansion mismatch between the silicon carbide and the carbon-carbon substrate. To alleviate this problem, use is made of additional interlayers that oxidize to form a glass that can flow and seal cracks. Unfortunately, these glasses do not flow readily at intermediate temperatures, reducing their effectiveness over part of the temperature range of interest. Recent advances in coating technology have improved the situation and small coated coupons have withstood the cyclic-temperature loading typical of a NASP environment. These improved protection schemes have yet to be scaled up to the large, complex-shaped components needed for NASP.

CERAMIC-MATRIX COMPOSITES

Like carbon-carbon composites, ceramic-matrix composites have the potential for use at temperatures in excess of 1300°C, with the added advantage of a much higher degree of inherent oxidation resistance. Unlike the carbon-carbon materials, they are not as mature as a class of structural materials and do not enjoy the same broad base of manufacturing experience. They have not been as widely used and they have limitations when it comes to using them for long times at the higher temperature ranges.

There are two general classes of ceramic-matrix materials that may be important for NASP: glass-ceramic-matrix composites, useful up to temperatures of about 815°C, and advanced ceramic-matrix composites, potentially applicable at much higher temperatures. Glass-ceramic-matrix composites are relatively well characterized and can be fabricated into product forms such as honeycomb-core panels, truss-core panels, and other complex shapes. Advanced ceramic-matrix materials--such as silicon carbide fiber reinforced silicon carbide (SiC/SiC)--are not as mature, principally because of the lack of a fiber that has sufficient stability in the matrix when exposed for long times above 1000°C. Improvements are being made in these materials, and large, complex-shaped demonstration components have been manufactured by specialist companies. A particular interest in the ceramic-matrix materials for NASP stems from their inherent resistance to hot hydrogen and they would be useful for actively cooled engine components..

BERYLLIUM ALLOYS

Beryllium is a commercially available material that possesses the advantages of low density, high elastic modulus, and very good thermal conductivity. Its disadvantages include poor toughness characteristics, crystallographic-texture-sensitive properties, a limited use-temperature of about 540°C, and environmental concerns associated with the toxic nature of the oxide. In spite of its problems, beryllium is successfully used in a wide variety of applications and there is a considerable body of experience concerning its fabrication and handling.

In addition to the benefits of light weight, its thermal conductivity characteristics make it particularly useful for structural components that are designed to transfer heat efficiently from one location to another. For NASP, the beryllium would be used primarily in heat exchangers or actively cooled engine panels, where it would be in sheet form in honeycomb-core or truss-core panel structures that would contain integral cooling passages within the structure.

COPPER-MATRIX COMPOSITES

Because the NASP vehicle will make extensive use of actively cooled structure, there is a particular interest in high thermal conductivity materials, including copper-matrix composites. Copper itself has a good thermal conductivity but is heavy and its upper use-temperature is limited by its low mechanical properties. Pitch-based, high modulus graphite fibers have excellent thermal conductivity--better than the copper itself in the direction of the fiber--and the addition of these fibers to copper reduces density, increases stiffness, raises the use-temperature, and significantly improves thermal conductivity in the direction of the fibers.

One approach to the fabrication of these composites starts with a process that places a layer of copper around each fiber in a graphite fiber tow. The coated fibers are subsequently packed together and hot pressed into a fully dense material containing a high volume percent of fibers. In practice, cross-plied lay-ups will be used to tailor the thermal conductivity and compensate for the directional effects of the fiber.

Additional work in this general area addresses discontinuously reinforced copper composites. These are made by adding alloying elements such as niobium to the copper and applying appropriate processing methods to form a very fine dispersion of the alloying addition. In this way it is possible to strengthen the material without lowering the conductivity of the matrix.

COATINGS

Coatings will play an important role for all materials used in the NASP airframe and engines and are a key part of the development activities for each material system. They can perform several critical functions, including control of temperature and protection against the environment.

For temperature control, they are designed to have high emissivity and to be noncatalytic to the recombination of the dissociated gases present in the hypersonic airflow across the skin. This can lead to a reduction of several hundred degrees in surface temperature. For oxidation resistance, they can provide a suitable barrier that prevents contact of hot oxygen with the underlying material.

The coating issue unique to NASP arises from the need to protect the materials against the effects of the hydrogen used for cooling. Hydrogen diffuses readily through many materials and can form brittle compounds within the material. The development of hydrogen barrier coatings is a critical challenge, especially coatings that are thin, lightweight, resistant to damage, and can be applied to complex shapes, including internal passages. Successful coatings most likely will incorporate multilayer protection schemes involving several thin layers of materials, each performing a contributing function.

Discussion

BOURY

You have shown a structure of metallic tube in carbon-carbon. Have you noticed some problem of thermal contact between these two materials?

AUTHOR'S REPLY

Yes, there is a problem. There is an expansion mismatch between the materials. We need to have very close contact. We have no solutions with confidence.

STOLLERY

Could you say something about the fatigue life that is expected of modern carbon-carbon material? Engine manufacturers say that in a few years we will have entirely non-metallic engines.

AUTHOR'S REPLY

It is a question of trading off various properties. We can improve fatigue performances in titanium aluminides at the cost of strength. We have to achieve a balanced set of properties. The question of fatigue of carbon-carbon is a different kind of situation. It is not a traditional material. It has to be handled somewhat differently. How do we detect a flaw in these materials?

OBSERVER (BRITISH AEROSPACE)

What are the difficulties to impregnate these materials with optical fibers?

AUTHOR'S REPLY.

The problem is the survival of these fibers during the material autoclave process.